Synthetic Aperture Sonar Forward Modeling and Inversion

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LONG-TERM GOALS

Current and future high-resolution MCM systems such as Synthetic Aperture Sonar are actively being developed. Unfortunately, this development is proceeding in many cases without a solid understanding of how environmental effects might degrade performance or how data inversion can be used to extract information about the environment. While these systems have been largely successful in achieving their goals of producing high-resolution imagery (on the order of square centimeters), there has been little effort in linking scattering physics to both the mean levels and statistics of the resulting sonar returns seen in the images. This type of knowledge is crucial for producing both realistic forward and inverse models.

The long-term goals of the present research are to develop and validate physics-based models and inversion tools relevant to current and future synthetic aperture sonar systems. The influence of the properties of the boundaries to the scattered envelope statistics will be examined in detail as will methods to invert system data for environmental parameters. This study will yield an improved understanding of the link between environmental parameters and system factors which contribute to SAS image statistics, as well as models and methods for characterizing, predicting and mitigating environmental effects. This effort may lead to improved methods for environmental characterization (i.e., 'through-the-sensor' inversion of seafloor properties), have direct application to performance prediction, and possibly provide guidance for adaptive strategies for speckle reduction based on the operational environment.

OBJECTIVES

The importance of the present work lies in the ability to link SAS image statistics to measurable environmental properties such as seafloor roughness. In conjunction with sonar system parameters, this link will provide the foundation necessary for solving several important problems related to the detection of targets with SAS. The direct link between system and environmental parameters via scattering models to the statistical distributions will allow: performance prediction for different systems based on environmental properties, extrapolation of performance to other systems/bandwidths, and optimization of system parameters such as frequency/bandwidth to the local environment.

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Concisely the proposed objectives are:

1. Examine relationships of acoustic scattering properties (sediment interface and possibly volume for low-frequency systems) to SAS mean levels and statistics;

2. Develop predictive physics-based forward models of mean levels and statistics relevant to SAS;

3. Develop inversion tools for estimating seafloor properties based on forward models;

4. Validate forward models and inversion results against at-sea experimental data.

APPROACH

Work has been conducted recently at the Applied Research Laboratory – Penn State University (ARL-PSU) to characterize and model high-frequency scattered amplitude statistics of SAS imagery as a function of resolution, relationship to correlated seafloor structures (ripples) and propagation conditions. Work conducted with Peter Gough at the University of Canterbury in Christchurch, New Zealand, has also shown promising initial results on the possibility of inverting SAS data for large scale 2-dimensional height fields. As a follow on, the proposed research program intends to increase our understanding of how acoustic scattering processes impact SAS data in terms of both mean levels and statistics. Knowledge gained will be included in models aimed at aiding in the prediction of environmental effects on current and future MCM acoustic systems and on inversion for environmental parameters. These goals will be achieved through a close association with current PIs and projects being performed by the NSWC-Panama City. Model development will be guided by feedback from real data collected by the NSWC-Panama City.

Initial focus will be on acoustic characterization and modeling of speckle in images of ripple sandy seafloors and we will later look at more complicated scattering scenarios (e.g. seagrasses, rocky outcrops, and possibly sediment volume effects). Collaboration with the NSWC-PCD will facilitate use of their quality SAS data and results will be fed back into their program. Inversion of component forward models will also be a main priority.

WORK COMPLETED

During FY2011, a wide variety of topics were investigated, some a continuation of work begun in FY10. Work on understanding the effects of random roughness on texture statistics was continued. One interesting result found during this work was that in some cases speckle that appears non-Rayleigh is in reality caused by random roughness and can be used to estimate random roughness in terms of rms slope/height from the statistics of speckle. A recent NSCW pond experiment performed in August, 2011, will be used to test this type of inversion measurement. We also learned that a Lambertian shape for the scattering strength curve at low grazing angles provided better a fit to scattering statistics data than first-order perturbation theory or the lowest-order small slope approximation curves.

Work was performed with graduate student Dan Brown to understand speckle statistics for very wideband systems (those with a bandwidth to center frequency greater than 1). Numerical models showed that speckle still be Rayleigh distributed even for cases when the theoretical resolution became smaller than a wavelengh. This result wasn't obvious or intuitive and data from a recent experiment at the NSWC test pond should help in clarifying this outcome. Work was performed with graduate

student Derek Olson on developing a method for in-the-field pseudo-calibration for uncalibrated SAS systems which uses the 'known' scattering strength of a uniform area (sand, rock) to estimate the combined transmit/receive response of the imaging system (including effects of SAS processing). Calibrated systems will allow areas to be mapped for scattering strength, slope, etc. and should aid ATR.

RESULTS

A theoretical framework was established within which to interpret the effects of intensity scaling of speckle on the statistics of SAS images. The validity of the theoretical results was investigated by application to real data. Data from the NATO Undersea Research Centre (NURC)'s MUSCLE AUV mounted SAS systems were analyzed and compared to effective *K*-distribution shape parameter predictions based on the scaled-speckle model. Data came from an experiment which took place near Tellaro, Italy off the Ligurian coast and was obtained on homogeneous silty-sand seafloor areas with varying degrees of topographic roughness. The top image in Fig. 1 displays a larger variation in intensity than the bottom image caused by a larger variation in seafloor slope. This strong variation in intensity will strongly influence the overall statistical characteristics of SAS images.

The scaled-speckle model was used to predict the effective shape parameter using roughness parameters and system geometries. If the scattered intensity differences due to slope changes are assumed to be approximately piecewise linear for each mean grazing angle, we can estimate the effective shape parameter as a function of mean angle (or equivalently range). Using Lambert's Law (or any physical seafloor scattering model) this assumption would only be valid for grazing angles approaching and exceeding approximately 30° if the range of relative angles with respect to the mean angle caused by the random seafloor slopes is small. With the scaling model and system geometry we can get a feel for the effects on effective shape parameter of the shape of the scattering cross section as a function of angle (or equivalently as a function of range for a fixed altitude).
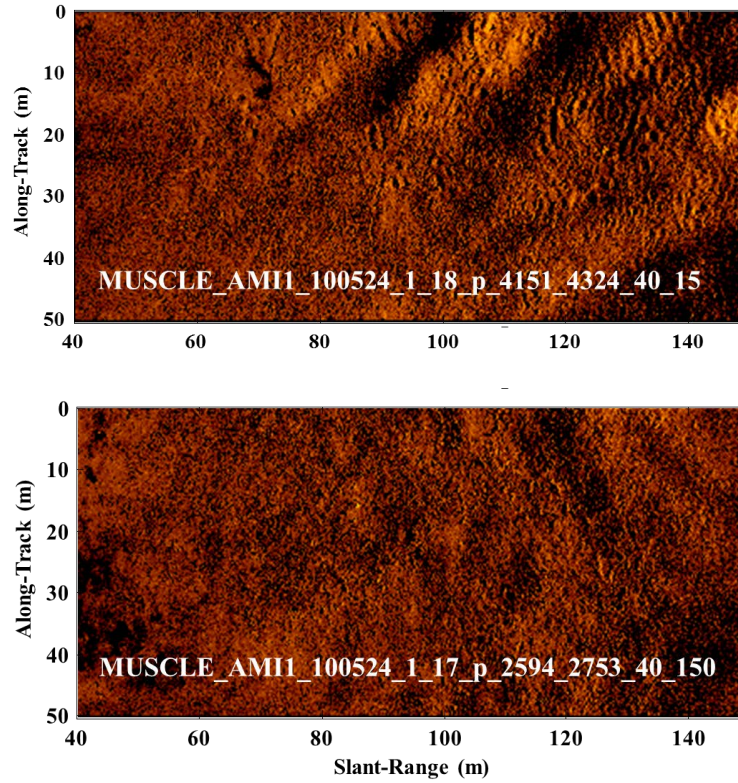
Figure 1. Example synthetic aperture images of random rough seafloors taken with the NATO Undersea Research Centre's MUSCLE system off the coast of Liguria, Italy. The top image appears rougher than the bottom due to increased slope variance.

Figure 2 shows a comparison between experimental estimates and model predictions of effective *K*-distribution shape parameter versus range for same the two MUSCLE data sets that were used to form the images of Fig 1. A sliding window 2.25 m wide in range is used in making the shape parameter estimates as a function of range. The effective shape parameter is seen to decrease as a function of range (the mean grazing angle decreases from approximately 14° at 40 m range to approximately 4° at 150 m range). It should be noted that it is not the underlying speckle statistics that are causing the overall decrease in the effective shape parameter versus range; it is the increasing mean slope of the scattering cross section at further ranges (or smaller mean grazing angles).

Also shown on Fig. 2 are scaled-speckle model predictions for rms slopes of 5.5^o and 7.7^o for the relatively smooth and relatively rough data respectively. Both predictions used a system height of 10 m and a speckle shape parameter of 100 (this large value of means the speckle is effectively Rayleigh distributed). It should be noted that the rms slope is over the entire 2.25 m x 50 m area for which the shape parameter estimate is formed. The model matches the data well showing the sensitivity of the result to rms slope. This sensitivity might allow seafloor roughness parameters to be easily inverted from SAS image data. Other statistical properties of seafloor roughness can be obtained if a model of seafloor roughness is assumed. If a seafloor exhibits power-law roughness spectra, as has been often found, rms height can be related to rms slope. A simulation which combines mean scattered levels calculated for a realization of the seafloor and Rayleigh speckle, is also shown on Fig. 2. The simulation used realistic power-law roughness parameters yielding the rms slopes as used in the scaled-speckle model (i.e., a spectral exponent of 3.25 and spectral strengths of 0.5x10-4 and 1.0x10-4

4

for smooth and rough cases respectively). Fig. 3 displays the same data as the top blue line in Fig. 2 along with model results assuming a Lambertian scattering surface and assuming first-order perturbation theory.
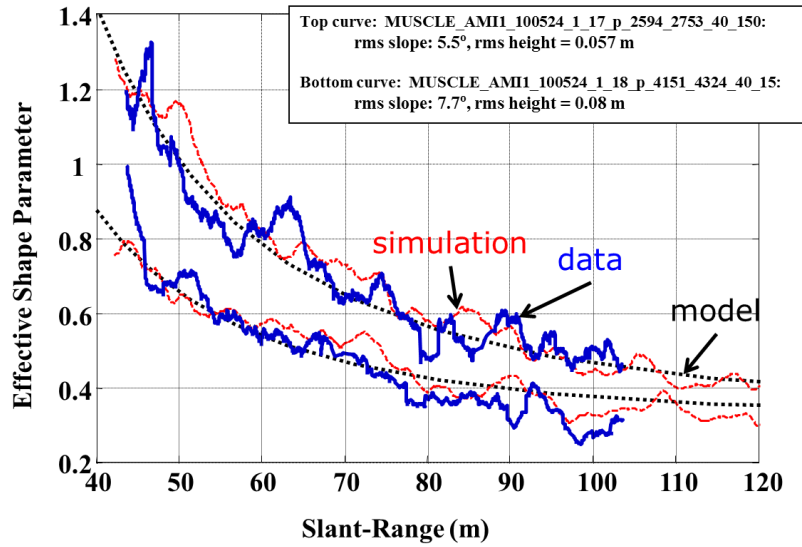

Figure 2. Experimental, simulation, and scaled-speckle model estimates of effective K-distribution shape parameter as a function of range. The experimental curves used the same data that was used to form the images in Fig.1.
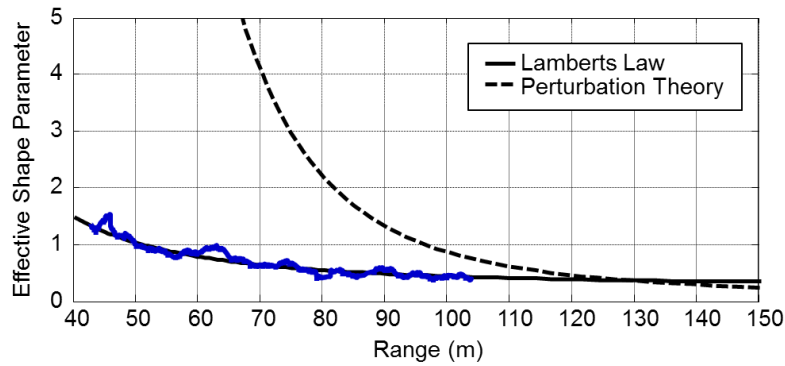

Figure 3. Experimental and scaled-speckle model estimates of effective shape parameter. The lower curves are the same as the upper curves on Fig.2 which use a Lambertian scattering model, and the upper curve assumes perturbation theory.

IMPACT/APPLICATIONS

SAS image statistics research is providing an improved understanding of the environmental parameters that affect high-frequency imaging systems. This study is leading to methods for modeling and

predicting these environmental effects that may be used to minimize their negative impact on detection and classification of targets on or near the seafloor in shallow water. Knowledge gained will help in the development of simulation tools, adaptive systems for sonar systems and rapid environmental assessment techniques for estimating environmental parameters for a given area.

TRANSITIONS

The models of that have been explored and developed are being incorporated when possible into the ARL-PSU Technology Requirements Model (TRM), a high fidelity, physics-based digital simulator. Discussions are also under way to include models into simulations of Synthetic Aperture Sonar being developed at NSWC-Panama City.

RELATED PROJECTS

A related ONR project (Grant N00014-10-1-0051) is Statistics of High-Resolution Synthetic Aperture Sonar Imagery: Physics-Based Speckle/Texture Analysis and Simulation managed by Jason Stack, code 321OE.

PUBLICATIONS

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